Proceedings of the 2020 Winter Simulation Conference
K.-H. Bae, B. Feng, S. Kim, S. Lazarova-Molnar, Z. Zheng, T. Roeder, and R. Thiesing, eds.

SCHEDULING AND SIMULATION IN WAFER FABS: COMPETITORS, INDEPENDENT PLAYERS OR AMPLIFIERS?

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ABSTRACT

This panel will discuss the inherent conflict between the application of (Discrete-Event) Simulation and Scheduling techniques to manage and optimise capacity and material flow in Semiconductor Frontend Manufacturing (wafer fabrication). Representatives from both industry and academia will describe advantages and shortcomings of the respective techniques, with a specific focus on challenges arising from the recent and anticipated future evolution of the nature of such manufacturing environments, and suggest solution approaches as well as research issues that need to be addressed.

1 INTRODUCTION – PETER LENDERMANN, D-SIMLAB TECHNOLOGIES

Discrete Event Simulation has been an important enabler for production planning and control in Semiconductor Manufacturing, in particular to study the dynamic behavior of wafer fabrication facilities (wafer fabs) which are subject to many random effects such as unscheduled equipment downs, or measurement outcomes, and where the interdependency between capacity and cycle time is an important consideration. At the same time – because of the pressure to utilize capital-intensive capacity as effectively as possible – the underlying paradigm for operating wafer fabs has typically been to load tools with lots from the queue in front of an equipment group as soon as a tool becomes available according to "real-time dispatch rules".

Over the past couple of decades Semiconductor Manufacturing has become more and more complex, especially in foundries, with more products, smaller volumes per product, faster-changing product mixes to be handled, and novel constraints on the product operations to be considered. In order to be able to manage the material flow of such complex, non-steady-state operations, dispatch rules would typically also have been adapted and become more elaborate over time.

At the same time, interdependencies in between different equipment groups such as queue time constraints or the potential availability of lots for batching have become more critical. However, if factors from immediate upstream or downstream equipment groups need to be taken into account, time horizons for decision-making beyond real time to at least a few hours need to be considered. As a result, the use of scheduling systems to run and optimise operations in wafer fabs has become widespread. Such systems have helped increase the utilization of critical capacity and meet due dates although any "optimal schedule" determined would still constitute a local optimum around the respective equipment group. Increasing automation efforts also have been an important driver and enabler of scheduling solutions for wafer fabs.

A finite scheduling horizon means that factors other than dispatch sequences also need to be considered for decision-making. Such factors comprise, for example, timing for Preventive Maintenance (PM) activities, setup changes, batch formation decisions, or qualification decisions for equipment. Since these factors could have equal or even more effect on KPIs such as capacity utilization, cycle time, or on-time delivery performance compared to dispatch sequences alone, they actually need to be considered as decision variables as well which in turn gives rise to the need to further increase the time horizon to be considered to up to several days.

In Semiconductor Manufacturing though, increasing the time horizon of a scheduling procedure is limited by frequent random events (such as the earlier mentioned) happening within the scheduling horizon that gradually invalidate the schedule. As such, a scheduling horizon of several days simply does not make sense. On the other hand, decisions such as PM timings also cannot be handled using conventional long-term simulation models because equipment downs are typically portrayed as random events in such a simulation model.

Where simulation is concerned, people have also been struggling because of the difficulty to validate a simulation model (a "Digital Twin") of a full wafer fab which is also partly due to the difficulty to portray human behavior and decision-making in such a simulation model. Moreover, scheduling and control systems are very difficult to portray in a simulation model with sufficient fidelity unless the simulation is slowed down to near real-time, which in turn limits the applicability of simulation-based decision making dramatically.

In the light of the challenges described, the question how the backbone of operations management in Semiconductor Manufacturing may look like in the future naturally arises:

- Either to schedule and reschedule operations at critical equipment groups on a regular basis with the objective to create local optima to squeeze more moves out of the available capacity around a particular equipment group. This would, however, make it very difficult if not impossible to run simulations with sufficient fidelity to make high-quality decisions, for example about PM timing, with potentially higher impact and to effectively manage the global performance of fab operations.
- Or to run fab operations with relatively simple dispatch and/or scheduling rules which would allow exploitation of more optimization potential from adjustment of decision variables such as PM timing through regular simulation-based optimization. This would, however, make it very

challenging to make non-intuitive scheduling decisions against implemented dispatch rules at a particular equipment group even though it would increase the performance at another equipment group (and the global fab performance) significantly.

In the setting of these challenges, this panel will discuss the needs for operating powerful scheduling systems and making use of "High Fidelity Digital Twins" to efficiently operate and optimize material flow in a wafer fab, future solution approaches, and research issues that need to be addressed.

2 STEPHANE DAUZERE-PERES, ECOLE DES MINES DE SAINT-ETIENNE

2.1 Limits of Optimized Scheduling and Simulation

Optimized scheduling requires advanced methods to be applied in complex equipment groups and to deal with the very large instances that can be found in semiconductor manufacturing with hundreds of machines and lots. Various types of hard and soft constraints must be considered, and multiple objectives must usually be optimized simultaneously, with various degrees of importance. As shown for instance in Knopp et al. (2017) and Klemmt et al. (2017), metaheuristics and constraint programming approaches have proved to be successful on instances of industrial sizes or in practical settings. However, even though the detailed schedule of lots can be optimized at equipment group level, it still remains unrealistic to determine a detailed schedule at fab level. Some approaches, such as the distributed one introduced in Mönch and Drießel (2005) for complex job-shop scheduling problems, have been proposed to schedule an entire wafer manufacturing facility. However, they usually consider a single objective function, whereas criteria can differ between equipment groups. Hence, the relevance of the proposed detailed global factory schedules still needs to be evaluated in industrial facilities.

Both simple dispatch rules or scheduling procedures embedded in simulation models allow the behavior of an entire semiconductor manufacturing facility to be evaluated. However, if advanced scheduling methods are actually used in the facility, at least in some equipment groups, then the evaluation might actually be skewed. As mentioned in Dauzère-Pérès and Lasserre (2002), "the scheduling module should represent as closely as possible the actual capacity of the workshop, and the scheduling techniques are part of that capacity. The better the jobs can be sequenced on the shop floor, the higher is the capacity." The "workshop capacity" is defined in this case as the throughput rate of the workshop, and not as the restricted definition of the available time of the machines. This is because machines are often idle in complex manufacturing systems, and advanced scheduling techniques help to reduce the idle times of machines and thus to improve the "effective capacity" of the workshop. Using industrial instances of the photolithography equipment group of a high-mix facility, Bitar et al. (2014) analyze the gain on the mean product cycle times of using an efficient optimization algorithm compared to a simple approach based on dispatch rules. The gain depends on the complexity and how heavily the equipment group is loaded. When the workload and the complexity are high, the gap on the mean product cycle times is larger than 20%, and is still larger than 5% if some constraints are removed.

2.2 Different Functions for Different Uses

With the availability of data and the increase of automated decision making in factories, optimized scheduling is becoming mandatory and critical to gain production capacity, in particular in high-mix manufacturing settings, where simple dispatch rules may lead to significant capacity losses. Complex constraints are very difficult, or even impossible, to handle with dispatch rules, leading to unrealistic dispatch decisions. Moreover, short-term schedules determined in each equipment group on a planning horizon of several hours help to plan other activities, such as the transportation and storage of lots or of auxiliary resources. However, global fab scheduling approaches are required to control the production flows between equipment groups, such as the one proposed in Bureau et al. (2007), to avoid the WIP to be imbalanced.

Simulation is important to analyze the impact of critical decisions through what-if analyses and to validate the relevance of novel approaches at factory level. The trends provided by simulation can be used for various strategic and tactical decisions, but might not be relevant to support operational decisions. Vehicle dispatching policies in an Automated Material Handling System (AMHS) are studied using a simulation model in Ben Chaabane et al. (2013) and Schmaler et al. (2017). The design of an Automated Guided Vehicle (AGV) transport system for the main auxiliary resources in the photolithography equipment group is analyzed using a simulation model in Ndiaye et al. (2016). Another example can be found in Barhebwa-Mushamuka et al. (2019), where a simulation model of wafer manufacturing facilities is used to show the efficiency of a global scheduling optimization model to control the Work-In-Process (WIP). Lima et al. (2019) are using a sampling-based approach, relying on a fast simulation of dispatch rules, to estimate the probability that a lot satisfies given time constraints before it is released.

2.3 Research Perspectives

I believe that a first challenge is to design and develop "Digital Twins" that would benefit from the advances of Discrete Event Simulation and/or agent-based simulation but also embed advanced scheduling algorithms. Because these algorithms are now available and are or will be used in factories, the Digital Twin will then represent the reality, in particular how lots are being processed on tools, and support various types of short-term decisions impacting the whole factory. Controlling the runtimes of the Digital Twin, which could be prohibitive, will be necessary.

However, I think that simulation using dispatch rules is sufficient for many types of decisions, in the short and medium term. Hence, a second idea is to study in which contexts and for which problems considering optimized scheduling in simulation models is relevant.

Generally speaking, the coupling of simulation and optimization is a very active field of research, with a specific track in the Winter Simulation Conference. Still, much remains to be done to combine simulation and optimized scheduling in the context of semiconductor manufacturing. For instance, as discussed for instance in Tamssaouet et al. (2018), a simulation model could be used to model the detailed behavior of a complex machine, and the resulting Digital Twin of the machine could be embedded in algorithms that schedule all the lots on all the tools in the equipment group.

3 LEON MCGINNIS, GEORGIA INSTITUTE OF TECHNOLOGY

Stuart Kauffman's book on complexity and chaos, "At Home in the Universe" (Kauffman 1995) makes a distinction between predicting and explaining, a distinction that is critical for this discussion. Because there are many sources of apparent randomness in a wafer fab, the terrible truth is that we will *never* be able to predict its future state with precision beyond a few minutes unless we can eliminate unpredictable or poorly predictable events. With that realization, what are the implications for how we should approach the problem of planning and control of wafer fabs? Having said that, some of the ideas presented in this section could be perceived as outrageous indeed!

Let us suppose for a moment that we could create an effective though deterministic Digital Twin of the wafer fab and thus could predict an *ideal* future, i.e., one where no randomness or unforeseen event upsets our plans and schedules. The value of this prediction is that it lays down a marker for where we want to be *and how we intend to get there*. Beyond that, it could allow us to analyze the state trajectory of the fab toward that future state, and in particular, to identify those potential contingencies (equipment failures, failed inspections, material handling delays, etc.) that would most upset our plans, which could include variability in transportation, storage/retrieval or lot handoff operations, queueing delays at inspection, unanticipated machine downtime, etc. If we could correctly identify and characterize these contingencies (perhaps using our vast prior experience) we might be able to "war game" them, making (standardized) contingency plans to respond to events that "might" occur in the future. As an example, what do we do with lots scheduled for a tool that has just been taken off-line for a breakdown repair? One can imagine a detailed decision tree approach to dealing with such contingencies. This approach is possible *if* we have the necessary knowledge about contingencies, *and* the technical and computational tools to support this "war gaming" approach – which by the way, could be done largely off-line. If not, there is a clear opportunity for useful research and development. Note that the technical and computational tools required would include at least a deterministic Digital Twin of the wafer fab incorporating *all* elements of the fab that influence state trajectory.

Simulation methodologists will no doubt be horrified at the notion of using a deterministic simulation as the baseline for war gaming possible contingencies, and insist that we must start from statistically valid predictions. But such outrage ignores the indisputable fact that no matter how many samples (simulation runs) we look at, we still do not know *exactly* which future will obtain. And the point of war gaming the contingencies is not to be prepared for *one* future, it is to be prepared for *any* future. Note also that every previously unencountered contingency becomes fodder for war gaming.

If we cannot predict the future state with precision, can we at least *explain* what we observe? For example, when a WIP bubble is observed, can we explain what caused it? When a non-bottleneck resource becomes a bottleneck because it has been idle for so long, can we explain why? Note that explaining such observations is much more than simply listing all the events that might have contributed. If one of those events does not *always* lead to the observed phenomenon, then we need to be able to explain that as well. Here is the key observation—the development of rules for "optimizing" scheduling in a process group or across a fab is founded on the intuition that certain observed behaviors can be explained, and those explanations are the basis for "rules" guiding decision-making.

Explaining observed phenomena requires a theory about the system that presents the phenomena, and a theory requires a model of the system in question. Newton's theory of universal gravitation was based on a model of two objects and posited a force of attraction between them; it was useful for explaining why apples fall toward the ground. What is the model of the wafer fab that we might use as the basis for positing theories that would help to explain the phenomena presented by the wafer fab?

So, whether we want to predict or to explain, we need a useful system model as a starting point. If we can neither predict nor explain, our efforts to plan and schedule will be forever frustrated.

3.1 On Digital Twins

The idea of the wafer fab Digital Twin is like the siren's call. "If GE can do it for gas turbines as in General Electric (2020), Lockheed can do it for an F-35 as in Mail Online (2020) and it can be done for integrated circuits as in Semiconductor Engineering (2020), then surely we can do it for wafer fabs." We should be asking ourselves why we have not been able to, so far (see the fascinating panel discussion from WSC 2019 as in Shao et al. (2019). To approach an answer, we will need to understand why and how Digital Twins in the produced system space have been possible.

Digital Twins for produced systems are the result of some very specific technological developments:

- Standards for specifying both components and systems: When the United States Department of Defense commissioned the development of the Hardware Description Language (HDL), it was to enable one vendor's product to be transitioned to another vendor for manufacturing in case the original supplier failed. But what HDL, and later VHDL (Very high speed integrated circuit Hardware Description Language), created was the foundation for design tools – without a standard way of specifying the produced system, generic "editors" are not possible.
- Interfaces to standard analysis methods: Once a standard specification of a produced system is available, a specific system specification can be translated into the required input for canonical analyses, such as circuit analysis, and thus circuit simulation. As a result, produced system designers have very inexpensive access to analyses that support design decision making, and developers have incentives to create new, better, more comprehensive analysis tools.

Representation standards are the cornerstone for all successful Digital Twin applications. Imagine what would be the state of integrated circuit design without VHDL? If every design house had to create their own (*ad hoc*!) tools to support design? Do you think we would have integrated circuits with billions of transistors?

3.2 The Challenge of Representation

What all successful Digital Twin applications have in common and what modern engineering design automation tools have in common is dependence upon an underlying Analysis Agnostic System Model (AASM). Whether designing integrated circuits, automobiles or airplanes, the designers work directly with such an AASM. If we aspire to be able to routinely create Digital Twins of Semiconductor Production Systems (SPS), then we need an AASM for them.

An AASM of the physical aspects of the SPS is intricate, but relatively straightforward, and the Discrete Event Logistics (DELS) framework provides an excellent starting point. What is much more challenging is modeling the control system, because it is not directly observable and thus models of it are virtually impossible to validate. In concept, the only way to realize a validated Digital Twin would be to integrate a computational model of the physical elements of the SPS with the actual control system. This is not a practical approach when people are making control decisions.

Again, the fundamental challenge is the absence of a suitable generic framework for conceptualizing, modeling, developing and implementing control systems for SPS.

3.3 Scheduling AND Simulation

For all the reasons mentioned in the Introduction, and more, there always will be limits to the predictive power of a wafer fab Digital Twin. Planning and scheduling always will be forced to manage contingencies. The fundamental question we should be addressing is "How do we get much smarter about and more capable in managing contingencies?" The answer must be built around an AASM of the wafer fab, and its use in the collection and post-mortem analysis of contingencies (using a simulation model!) to develop standard strategies for each class of contingency. If we can do that, then integrating factors like PM scheduling is at least conceivable. Otherwise, we will continue to see new and better *ad hoc* approaches, and discover their limitations.

4 LARS MÖNCH, UNIVERSITY OF HAGEN

4.1 Scheduling and Simulation as Amplifiers

The assignment of scarce resources to activities over time is called scheduling. Scheduling is a decision-making process that aims to optimize at least one performance measure while taking into account all relevant constraints (Pinedo 2016). On the one hand, scheduling is explicitly or implicitly associated with a finite scheduling horizon of positive length. Hence, a scheduling approach for a semiconductor manufacturing (wafer fabrication) facility typically considers several lots and tools at the same time. A scheduling technique is able to adapt to different system conditions. Most of the scheduling approaches are based on deterministic data. Therefore, it may be challenging to execute schedules in a wafer fab, a manufacturing system that is highly dynamic and stochastic.

Dispatching, on the other hand, selects a job that has to be processed next for a given available tool among the jobs waiting in front of this tool (or tool group) for processing. Dispatching can be considered as the limiting case of scheduling with a fixed resource assignment and a scheduling horizon which tends to zero. It becomes clear that dispatching is myopic by nature. The ability of dispatch rules to consider the situation on upstream and downstream tool groups is limited. Dispatching has a long tradition in semiconductor manufacturing (cf. Uzsoy et al. 1993; Mönch et al. 2013). It is still the tool of choice in many wafer fabs (Pfund et al. 2006). While at the beginning fairly simple dispatch rules are applied (Wein 1988), sophisticated rule-based dispatching systems are in place in wafer fabs over the years. Dispatching approaches are conceptually easy to understand, and they are robust to cope with changes in WIP, static priorities of the lots, and the machine environment of a wafer fab.

Until a decade ago, deterministic scheduling techniques seemed to be too computationally costly as compared to dispatching. However, with the recent dramatic increase in computer efficiency, scheduling methods for single tool groups or even certain work areas in a wafer fab have become more competitive (Mönch et al. 2011). It seems that especially time-limited mixed integer linear programming (MILP)-based approaches with a short scheduling horizon and frequent rescheduling are quite popular in wafer fabs (Ham and Cho 2014; Jung et al. 2015). Scheduling techniques are important to deal with highly-constrained problems, for instance, time constraints between the start of consecutive processing steps in semiconductor manufacturing (Klemmt and Mönch 2012) or for making batching- or setup-related decisions (Jung et al. 2014).

One open question is whether fab-wide scheduling approaches are practicable for a real-world wafer fab or not. Such a global scheduling approach has the advantage that factory-wide performance measures such as total weighted tardiness or cycle time can be optimized. While some of the fab-wide scheduling approaches, mainly based on disjunctive graphs and the shifting bottleneck heuristic are quite promising (Ovacik and Uzsoy 1998; Sourirajan and Uzsoy 2008), for instance, the one designed in the Factory Operations Research Center (FORCe) project (Pfund et al. 2008; Mönch and Zimmermann 2011), it seems that no full real-world implementation of such a system exists nowadays. In wafer fabs, it is often required to make scheduling decisions for processing of lots on tools in an integrated manner with other decisions, for instance for the automated material handling system (AMHS) or advanced process control (APC). While fully integrated scheduling approaches are designed for such problems in academic research labs (Driessel and Mönch 2012; Yugma et al. 2015), they often lead to high modeling and computational burden. In such situations, local scheduler for bottleneck equipment groups or work areas that are coordinated through a higher level decision support layer are more promising.

Coming back to the original question of this panel, in my opinion Discrete Event Simulation is an amplifier that might improve scheduling (and also dispatching) decisions and vice versa on the following levels (Fowler et al. 2006):

1. Simulation-based schedule generation, refinement, and optimization
2. Simulation used for parameter setting and problem instance generation for scheduling approaches
3. Simulation for emulation and evaluation of scheduling approaches.

On all levels, simulation is used to anticipate the behavior of the shop floor when making scheduling decisions. We will discuss the three levels in a point-by-point manner.

Simulation-based schedule generation, also known as simulation-based scheduling, refers to the situation where a simulation tool together with an up-to-date simulation model is applied to make scheduling decisions. The built-in dispatch rules of the simulator are used to compute a schedule with a horizon of several hours. Stochastic effects such as tool breakdowns are turned off due to the short horizon. An appropriate initialization of the simulation model is a non-trivial task. Once a schedule has been computed, it can be refined by taking into account additional resources, for instance secondary resources such as reticles. Their consideration requires some deterministic forward simulation. Simulation-based schedule optimization is based on the idea that the objective function of a scheduling approach is computed based on simulation by executing the schedule in a simulation model. The schedule is changed and the assessment via simulation is repeated. Note that this approach can also be used to discover dispatch rules via genetic programming (Hildebrandt et al. 2014).

Simulation can be used to set parameters in scheduling heuristics in a situation-dependent manner. In order to evaluate the impact of a concrete parameter setting, the schedules have to be executed in a simulation environment. This can be part of the training phase of Machine Learning approaches (Mönch et al. 2006). It is also possible to use simulation to generate problem instances for scheduling approaches that reflect the current load and due date setting in a wafer fab (Sourirajan and Uzsoy 2007).

Scheduling approaches for wafer fabs are mainly based on deterministic data. Simulation is used to allow for rolling horizon settings, i.e. instead of a single problem instance a series of interrelated instances is solved where the instances come from executing the schedule in a single scheduling epoch (Mönch and Zimmermann 2011). This allows assessment of the performance of a scheduling approach in a risk-free simulation environment before its deployment at the shop floor. Overall, we observe that scheduling and simulation can be seen as two sides of a coin.

4.2 Future Research Directions

A first important research direction is given by designing and assessing hierarchical approaches where the higher level is able to coordinate the lower level, i.e. the scheduling or dispatching level by appropriate instructions. Such an approach would allow the design of local schedulers. For instance, it would be interesting to explore the interface between production planning and shop-floor scheduling which is a significantly under-researched area. I also see the need to develop a better understanding of the feasibility of fab-wide, i.e. global scheduling approaches for wafer fabs. This includes a more in-depth investigation of integrated approaches with for instance, PM, AMHS, or APC. Another research avenue is given by designing and assessing scheduling approaches for local or global schedulers in wafer fabs where the considered machinery includes cluster tools. Cluster tools are special integrated machines for wafer processing in wafer fabs. Since wafers with different types of process steps can circulate in a cluster tool simultaneously, it can be regarded as a fully automated machine environment (Mönch et al. 2013). Cluster tools are used to maximize quality performance at the cost of very complex behavior. While there are many scheduling techniques known for scheduling of wafer movements inside a cluster tool, external cluster tool scheduling which aims for scheduling jobs waiting to be processed in front of a cluster tool is an under-researched area. This is a non-trivial task since several wafers are simultaneously processed in a cluster tool and the internal behavior of the cluster tool determines the completion time of these wafers. As a last direction, it seems desirable to better incorporate the stochastic behavior of lot arrivals into scheduling approaches for batch processing tools.

5 TINA O'DONNELL, SEAGATE TECHNOLOGY

5.1 Simulation and Scheduling

Simulation is currently employed to aid decision making in Seagate wafer fabs. Long term capacity planning, medium and short term fab utilization are the main areas of interest. Real-Time Dispatching (RTD) is a key driver in decisions and therefore is an essential input to Seagate's short term fab simulations. The goal is to ensure simulation models reflect the true conditions of the fab and dynamically change with minimal manual modification. Incorporating dispatch rules has allowed Seagate to use simulation for real time decision making. There are a number of areas that utilize simulation that include managing the scheduling of wafers, reticles and inputting expected behavior for optimization models. In addition, incorporating dispatch rules in simulation provide an opportunity to demonstrate the impact of exploratory rules without costing the factory in key KPIs.

Scheduling models assist in determining what is the next best batch to execute, however, events occur that no longer ensure feasibility of a schedule so modifications need to be made in real time. Variability that is inherent in wafer fabs is difficult to predict and plan for, therefore RTD has proved to be invaluable for speed of decision making. However, RTD only determines the local optima at tool level based on heuristic rules and does not look beyond the current conditions and moment in time. The development of optimized scheduling models using Mixed Integer Linear Programming (MILP) that consume simulation data has improved the KPIs of key toolsets at the local optima level.

5.2 Further Research Opportunities

The ability to determine the global optimized schedule for a multi-reentrant fab to meet the objective functions, for example, increasing throughput, reducing cycletime or ensuring customer requirements are always fulfilled is the ideal scenario. The solution is required to react to the very dynamic nature of semiconductor fabs and determine the optimal schedule as real-time as possible. There are a number of practical limitations that need to be addressed before this is achieveable.

- Model execution time: Currently RTD makes a good decision in a matter of seconds, whereas scheduling models usually require minutes of execution time. Increasing the complexity of the models by adding tools, dispatch rules and searching for the global optima for a full fab solution will inherently increase the execution time of the model.
- WIP and tool variability: The dynamic nature of the fab can cause the simulation and schedule to be out of date. The real-time component needs to be able to use this data and make a sub-optimal decision without incurring infeasible solutions.
- Digital Twin: Tooling is unique and can be difficult to model. RTD has specific rules for quality/batching or costing to help address this uniqueness of toolsets and positioning within the line. Incorporating all unique dispatch rules and factory events in simulation modelling would be key to creating a digital twin.

The use of static and dynamic planning tools to determine the capacity of the fabs is used within Seagate. This is an excellent tool for long term planning. Simulation models that incorporate RTD rules can provide a good metric of actual KPIs perform against simulated KPIs on a short term basis. There may be an opportunity using optimization to determine if we can increase the factory performance by understanding the true potential of the fab and validate Seagate's current planning tools. The ability to utilize an accurate factory digital twin will help long and short term decision making if modelling execution times meet the requirement of the requester.

6 GEORG SEIDEL, INFINEON TECHNOLOGIES

6.1 Dispatching and Scheduling in Simulation and Reality

At Infineon front end wafer fab simulation models are used to support operations and planning (Seidel et. al. 2017) and to carry out scenario runs to address strategic capacity planning and material flow related questions. There is always the challenge to provide a simulation model as close as possible to reality but with reasonable effort to maintain and to validate it.

One crucial simulation modelling aspect are the dispatch rules that are used within the simulation model to determine which of the lots, waiting in a queue in front of equipment, will be processed next. Semiconductor fabs use typically many different dispatch rules, local and global ones, to optimize the fab performance. In the past years the importance of scheduling has been growing as well. More and more equipment or equipment groups are controlled through scheduling rather than dispatching. Mixed integer linear programming (MILP) and constraint programming (CP) based scheduling can be used to improve fab performance, at least locally (Klemmt et. al. 2017).

Infineon simulation models contain global dispatch rules as well as local ones. Not all local dispatch rules are used in the models for reasons of simplicity and because the impact on simulation results are considered to be low. Reasonable accuracy levels for simulation results have been achieved without incorporating all dispatch rules. The same holds true for equipment groups where scheduling solutions are used in reality. Instead of representing these scheduling solutions in the simulation, global dispatch rules are used instead.

Simulation accuracy is calculated and monitored for Wafer In, Wafer Out (Moves) and WIP for each equipment group daily or weekly. The absolute gap between predicted values by simulation and real values from the fab, divided by the maximum of the values is calculated for each model, as soon as the real values are available. A model accuracy is also calculated by using a move weighted average over all equipment groups and days or weeks. Model accuracies around 10% are considered acceptable. The best accuracies are reached for automatically generated models without any fine tuning are around 5%. For some models for which a lot of effort was spent in fine tuning an accuracy of 1-2% was reached.

6.2 Future Research Directions

Incorporating scheduling solutions into a simulation model can answer questions such as: What is the impact of local optimization of equipment or work center scheduling on the global fab performance? Can the fab improve further by using a global scheduling algorithm? How is the impact on simulation accuracy if global dispatch rules are used in the simulation instead of the scheduling solutions used in reality? It is desirable indeed to get answers to these very interesting and relevant questions.

6.3 Practical Limitations

Calculation of an executable and optimized schedule in a real fab is challenging. Data accuracy and availability must be extremely high. Optimized scheduling provides much better results compared to dispatching only at equipment groups where complexity is high. For example, equipment groups with high dedication level, comprising batch tools and/or cluster tools and equipment with different processing speeds are worthy targets for improvement by scheduling. Even with the increased computational power in the last years it takes some time to calculate an optimal schedule for a complex equipment group.

Generation of a simulation model for a whole frontend fab requires some sort of abstraction. I do not see any practical way to incorporate complex scheduling algorithms with the needed high data granularity (e.g. modelling of detailed cluster tool behavior, assumption of future lot arrivals to improve batching efficiency, etc.) in a fab model, and at the same time keeping the simulation runtime low and the model reasonably well maintainable. Reasonable simulation accuracy levels have been achieved on the fab level by using global dispatch rules in simulation instead of the real scheduling solutions. This indicates that the impact of existing scheduling algorithms is small, at least on fab level. This may change in the future if more sophisticated scheduling solutions for combinations of several equipment groups or even the whole fab will be available.

7 PHILIPPE VIALLETELLE, ST MICROELECTRONICS

7.1 Some History: At STMicroelectronics WIP Management Started with Simulation

At STMicroelectronics (ST), twenty years ago, simulation was used to drive execution in all frontend fabs. A global simulation was run over the fab, using known PM planning and detailed modelling of critical (bottleneck) toolsets, hence lots' priorities. The result of the simulation was then used to allocate a priority bonus to the lots having the largest progression in terms of number of steps processed. The result was also used during daily production meetings to analyze the biggest gaps vs. reality. Simulation was defined as the reference and not achieving the forecast was considered as low performance. Moreover, as simulation results were known at shift start and made accessible to shop floor, production personnel naturally tended to follow the simulation outputs, thus enabling a very good accuracy of the model!

The problem with this approach was twofold: 1) As simulation was used in a push mode, it did not guarantee on time delivery and 2) Lots' priority values extrapolated from the simulation were in fact just reflecting the behavior of the (simple) dispatch rules used in the simulation. While the first issue was (partially) overcome by assigning priorities according to lateness vs. target due date, the second issue was only marginally addressed through the engineering of ever more sophisticated dispatch rules (still in the simulation). But with the growing complexity of production processes, the intrinsic limitation of simulation became obvious. Because the only tools where priorities are needed for lot dispatching are bottlenecks (if no WIP is waiting in front of the tool, just FIFO can be used!), then why not run the dispatch rules near real time? This would allow much more precise WIP hypotheses than in the simulation (lots are already at step), hence more sophisticated dispatch rules and heuristics (because computational time was no longer a limitation).

Several generations of dispatch rules and engines were then developed and pushed to production, before being replaced by "better" or "simpler" ones, depending on the product mix but also fab loading and management belief. As most of the ST fabs still largely rely on operators for lot dispatching, the availability of lots seen by the Factory Information and Control System (FICS) may be seriously challenged by the ability of one human operator to find the right lot and bring it to the right tool at the right time. So, when fab loading was low, most of the sophisticated rules may be simplified (to get a more actionable system for management). And then, when fab loading was high, simplified dispatch rules were found to perform poorly. So these rules had to be reengineered in order to take into account new constraints.

7.2 Real-Time Scheduling and Dispatching

With the arrival of 300mm and Automated Material Handling Systems (AMHS), dispatching and scheduling have become almost mandatory. Lots – and information about these lots, hence the tools processing or being able to process them – being available at any time, tenths of dispatch rules can be triggered every second, as soon as a new "event" is coming under the radar of the FICS. This allows to considerably reduce the variability of interarrival times (at least when linked to human availability), hence reduce cycle times. Nevertheless, while the deployment of dispatch rules on "simple" toolsets easily demonstrates clear benefits, their implementation on toolsets more sophisticated in terms of processing scenario may prove cumbersome, especially in the context of European waferfabs. In Crolles300 for example, the automation of the Ion Implantation area initially required nearly 20 (twenty) intricated dispatch rules. The dispatching scheme has been simplified since, but this clearly demonstrated the need for smarter approaches when addressing toolsets more sophisticated in terms of processing scenario such as Photolithography or Diffusion / Thermal Processing.

The deployment of schedulers based on optimization techniques has already brought benefits in terms of toolset productivity (OEE) and the cycle time of critical lots. But for "multi-purpose / multi-generation" European fabs, the price to pay for such developments is quite high. Given the variety of technologies produced, the diversity of tools used in a single process area (e.g. heterogeneous clusters) and local singularities brought by specific engineering constraints or control procedures, real optimization may often be impossible. Furthermore, as line technicians may develop real expertise over time, they always may challenge some specific iterations of the scheduler on critical toolsets. And they are often right! Fortunately for the system, they are not able to do it 24/7 all over the production toolset. Moreover, the root cause of such sub-optimality is exogenous to the system: Technicians may take into account some information that is (still) not known by the system. And what is not known by the system cannot be taken into account as decision criteria.

Coming to support dispatching and scheduling, simulation may be used to provide different kinds of very valuable information: On lots arriving soon to complete batches or series, on reticles that will be used in the next period, on recipes to be validated in order to improve the flexibility of the toolset (i.e. degrees of freedom for scheduling), etc. Some of these results are even more interesting when taken "negatively": Knowing that no lot will come to complete this batch within the next 48 hours is a very valuable (and generally highly reliable) input. Nevertheless, that is mainly the low reliability of simulations that prevent their wide utilization in real-time WIP management decisions. So increasing the accuracy of so-called Digital Twins would greatly benefit scheduling and dispatching, especially when addressing challenges such as the management of queue time constraints for example (see for instance Lima et al, 2019 and Lima et al., 2020).

7.3 The right tool for the right task

As for sophisticated dispatching or scheduling engines, the main roadblock to real Digital Twins is the level of details such models would require for a holistic approach of a wafer fab. And this is especially true for a majority of wafer fabs over the world. As these factories were built years ago, their personnel developed significant skills and know-how. And what is not in the system is not known by the system. So, just think of the effort that would be needed for a model encompassing the behavior of lot transportation and storage system, the internal logic of various types of heterogeneous multi-chamber and multi-purpose cluster tools, the decisions made on lots depending on the measurement made (or not when sampling is done according to risk evaluation on process tool or control loops for example), the outcome of maintenance activities (also depending on the availability and skills of qualified technicians, relevant spare parts or consumables and test wafers, hence measurement tool to re-qualify the machine), or simply the availability of an operator when a manual intervention is needed.

When considering European front-end fabs, this holy grail is still very far and even the most advanced models must be built on strong hypotheses, very often relying on strong approximations. Forecasting models will then most of the time rely on statistics (average process times, distribution of failures, average cycle time, etc.) in order to provide a best guess estimation for the coming days. Latest advances were based on the use of multi-models approaches as for weather forecasting may be a solution: Various models are run on the same input data and/or the same model is run on different scenarios. When they all converge, the confidence is high, however, when they diverge then the decision is left to human judgment. Naturally, simulation may also be used to test and evaluate different options in different situations. In that sense, it may be used to reinforce dispatch rules and scheduling engines or algorithms. Such approaches may even be used to enable the automatic adjustment of dispatching parameters to factory situation, using AI to identify such situations. This is a very promising research axis.

For the time being, at STMicroelectronics, while the use of dispatching is clear, simulation may be used for two main purposes: 1) Forecasting in order to improve scheduling and 2) Reproducing a known behavior in order to evaluate potential impacts of one or several modifications (i.e. what-if analysis). While the first one is generally used on a wide perimeter (e.g. factory level), the second one is focusing on a much narrower scale such as recent studies done on the operators flows during shift changes in order to guarantee social distancing during the latest COVID outbreak.

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